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IN THE SPECIFICATION:

Please amend the specification as follows:

[0003] The ultrafine crystal layer refers to a layer with crystal grains each having a size of from 100 nm to 1 μm, while the nanocrystal layer refers to a layer with crystal grains each having a size of not larger than ~~100 um~~ 100 μm. The ultrafine crystal layer has characteristics suitable for a machine component, such as its hardness higher than that of its base material and its high compressive residual stress. Similarly, the nanocrystal layer has characteristics suitable for a machine component, such as its hardness much higher than that of its base material, its difficulty of grain growth even at a high temperature and its high compressive residual stress.

[0005] Thus, there are proposed various techniques for forming the ultrafine crystal layer and the nanocrystal layer (hereinafter referred to as "nanocrystal layer or the like") in a surface layer portion of a metallic material. For example, in JP-2003-39398A, in the paragraph [0001] and Fig. 2, there is proposed a technique for causing a protrusion formed in a distal end surface of a metal weight, to collide with a portion of a surface of a metallic product, so as to form the nanocrystal layer or the like in the portion of the surface of the metallic product ~~(Patent Document 1)~~.

[0006] Further, as another conventional technique, there is a technique using a shot peening. Fig. 16 is a schematic view showing the shot peening. This shot peening is, as shown in Fig. 16, arranged to cause hard particles G such as steels and ceramics to collide with a portion of a working surface 101a of a metallic material 101 at a high velocity, by using an ejection pressure of a compressive air ejected from an ejection device 100. The collision causes the portion of the working surface 101a to be plastically deformed, and accordingly forms the nanocrystal layer or the like in the portion of the working surface 101a.

~~Patent Document 1: JP-2003-39398A (Paragraph [0010], Fig. 2, etc.)~~

[0010] Further, in the above-described conventional techniques, since the nanocrystal layer or the like is formed owing to the plastic deformation of the surface of the product with which the protrusion or the hard particles G are caused to collide, the formed surface of the nanocrystal layer or the like ~~is made~~ becomes rough, and cannot ~~be provided by~~ achieve a smoothly finished surface. In addition, there is another problem that the nanocrystal layer or the like cannot be homogeneous in its entirety.

[0011] For example, in the technique for colliding with the protrusion of the metal weight, there ~~is~~ arises a difference, between a center portion and a peripheral portion

of the protrusion, with respect to a collision pressure acting on the product surface. This difference causes the nanocrystal layer formed in the collision surface of the product, to be uneven in a radial direction of the protrusion, with respect to its thickness and characteristics. Further, in the technique using the shot peening, the hard particles G ~~can not~~ cannot be caused to collide evenly with an entirety of the inner circumferential surface of the hole, so that the nanocrystal layer is likely to be concentrated in a portion of the inner circumferential surface that is adjacent to an opening of the hole, rather than in a portion of the inner circumferential surface that is adjacent to a bottom of the hole.

[0013] On the other hand, the present inventors, ~~as an outcome of their assiduous studies of~~ to overcome the above-described problems, proposed a technique for forming the nanocrystal layer or the like that is configured to have a shape of the product, by a machining operating such as drilling operation (in Japanese Patent Applications No. 2003-300354 and No. 2004-13487, ~~either of which has not been yet laid open~~ Laid Open Publications No.2005-69377 and No. 2006-312202, respectively), and enabled an industrial use of the nanocrystal layer or the like. However, in this technique, the machined surface is given a high distortion while a material temperature of the machined surface is being held low.

Therefore, ~~where~~ when the machining is performed on a workpiece of a material having a high hardness, a load exerted on a machining tool is increased. Thus, in this technique, there is a problem that the tool could be broken or a problem that the machining operation could not be carried out.

[0015] For achieving the object, a first aspect of the invention defines ~~an ultrafine crystal layer forming~~ a process of forming an ultrafine crystal layer in a surface layer portion of a surface of a workpiece constituted by a metallic material, by performing a machining operation on the surface of the workpiece using a machining tool, so as to impart a large local strain to the machined surface of the workpiece, wherein the machining operation using the machining tool causes the machined surface of the workpiece to be subjected to a plastic working ~~that causes the machined surface of the workpiece to have~~ with a true strain of at least 1.

[0016] According to a second aspect of the invention, in the ultrafine crystal layer forming process defined in the first aspect of the invention, the machining operation using the machining tool is performed with a material temperature at the machined surface of the workpiece being held lower than a predetermined upper limit temperature, wherein the predetermined upper limit temperature is, ~~where~~ when the workpiece is constituted by a steel material, an Ac1 transformation point of the steel material, and wherein the

predetermined upper limit temperature is, ~~where~~ when the workpiece is constituted by the metallic material other than the steel material, substantially half a melting point of the metallic material as expressed in terms of absolute temperature.

[0017] According to a third aspect of the invention, in the ultrafine crystal layer forming process defined in the first aspect of the invention, the machining operation using the machining tool is performed with a material temperature at the machined surface of the workpiece being held within a predetermined temperature range, wherein the predetermined temperature range is, ~~where~~ when the workpiece is constituted by a steel material, not lower than an Ac1 transformation point of the steel material and is lower than a melting point of the steel material, and wherein the predetermined temperature range is, ~~where~~ when the workpiece is constituted by the metallic material other than the steel material, not lower than substantially half a melting point of the metallic material as expressed in terms of absolute temperature and is lower than the melting point of the metallic material.

[0018] According to a fourth aspect of the invention, in the ultrafine crystal layer forming process defined in the third aspect of the invention, ~~where~~ when the workpiece is constituted by the steel material, after the machining operation using the machining tool has been performed, the

machined surface of the workpiece is cooled at a rate higher than a cooling rate that is required for hardening the workpiece.

[0019] According to a fifth aspect of the invention, in the ultrafine crystal layer forming process defined in any one of the second through fourth aspects of the invention, the machining operation using the machining tool is performed, such that a material temperature at the machined surface of the workpiece is held lower than the predetermined upper limit temperature or held within the predetermined temperature range, and such that a material temperature at a non-ultrafine crystal layer which is ~~provided by~~ in a lower layer portion of the machined surface or which is ~~provided by~~ in a surface layer portion in the neighborhood of the machined surface is held at least about 500 C° for a ~~length of~~ time ~~that is~~ not ~~larger~~ longer than about 1 second, for providing the non-ultrafine crystal layer with a hardness that is about 80 % as high as a hardness of a substrate of the workpiece.

[0021] A seventh aspect of the invention defines a ~~machine component producing~~ process of producing a machine component constituted by a metallic material and having a surface layer portion that is at least partially provided ~~by~~ with an ultrafine crystal layer, wherein the process includes at least ~~an ultrafine crystal layer forming~~ a step of forming the ultrafine crystal layer in the machine component by the

ultrafine crystal layer forming process defined in any one of the first through fifth aspects of the invention.

[0022] An eighth aspect of the invention defines a ~~nanocrystal layer forming~~ process of forming a nanocrystal layer in a surface layer portion of a surface of a workpiece constituted by a metallic material, by performing a machining operation on the surface of the workpiece using a machining tool, so as to impart a large local strain to the machined surface of the workpiece, wherein the machining operation using the machining tool causes the machined surface of the workpiece to be subjected to a plastic working ~~that causes the machined surface of the workpiece to have~~ with a true strain of at least 7, and is performed with a material temperature at the machined surface of the workpiece being held within a predetermined temperature range, wherein the predetermined temperature range is, ~~where~~ when the workpiece is constituted by a steel material, not lower than an Ac1 transformation point of the steel material and is lower than a melting point of the steel material, and wherein the predetermined temperature range is, ~~where~~ when the workpiece is constituted by the metallic material other than the steel material, not lower than substantially half a melting point of the metallic material as expressed in terms of absolute temperature and is lower than the melting point of the metallic material.

[0023] According to a ninth aspect of the invention, in the nanocrystal layer forming process defined in the eighth aspect of the invention, wherein the machining operation using the machining tool is performed, such that a material temperature at the machined surface of the workpiece is held within the predetermined temperature range, and such that a material temperature at a non-nanocrystal layer ~~which is provided by~~ in a lower layer portion of the machined surface or ~~which is provided by~~ in a surface layer portion in the neighborhood of the machined surface is held at least about 500 C° for a ~~length of~~ time ~~that is~~ not ~~larger~~ longer than about 1 second, for providing the nanocrystal layer with a hardness that is about 80 % as high as a hardness of a substrate of the workpiece.

[0024] A tenth aspect of the invention defines a ~~nanocrystal layer forming~~ process of forming a nanocrystal layer as a fine crystal grain layer in a surface of a workpiece constituted by a metallic material, wherein the process includes a step of performing a machining operation on the surface of the workpiece using a machining tool, so as to impart a large local strain to the machined surface of the workpiece, for forming the nanocrystal layer in a surface layer portion of the machined surface of the workpiece.

[0025] According to an eleventh aspect of the invention, in the nanocrystal layer forming process defined in the tenth

aspect of the invention, wherein the machining operation using the machining tool causes the machined surface of the workpiece to be subjected to a plastic working ~~that causes the machined surface of the workpiece to have~~ with a true strain of at least 7, and is performed with a material temperature at the machined surface of the workpiece being held ~~not higher~~ lower than a predetermined upper limit temperature, wherein the predetermined upper limit temperature is, ~~where~~ when the workpiece is constituted by a steel material, A1 and A3 transformation points of the steel material, and wherein the predetermined upper limit temperature is, ~~where~~ when the workpiece is constituted by the metallic material other than the steel material, substantially half a melting point of the metallic material as expressed in terms of absolute temperature.

[0028] A fourteenth aspect of the invention defines a machine component constituted by a metallic material and having a surface layer portion, wherein the surface layer portion is at least partially provided ~~by~~ with a nanocrystal layer formed by the nanocrystal layer forming process defined in any one of the eighth through thirteenth aspects of the invention.

[0029] A fifteenth aspect of the invention defines a ~~machine component producing~~ process of producing a machine component constituted by a metallic material and having a

surface layer portion that is at least partially provided ~~by~~ with a nanocrystal layer, wherein the process ~~included~~ includes at least a ~~nanocrystal layer forming~~ step of forming the nanocrystal layer in the machine component by the nanocrystal layer forming process defined in any one of the eighth through thirteenth aspects of the invention.

[0030] In the ultrafine crystal layer forming process defined in the first aspect of the invention, since the ultrafine crystal layer is formed in the surface layer portion of the machined surface by performing the machining operation using the machining tool, it is possible to ~~restrain~~ solve the problems, encountered in the conventional techniques, that portions of a workpiece in which the ultrafine crystal layer can be formed are limited depending upon a shape of the workpiece and that the thickness and characteristics of the ultrafine crystal layer are not ~~uniform,~~ uniform. Consequently, the ultrafine crystal layer forming process provides an effect that makes it possible to stably form the ultrafine crystal layer ~~forming process~~ in the workpiece such as a machine component.

[0032] Further, in the conventional techniques, ~~where~~ when the ultrafine crystal layer is to be formed over a wide area, the collision of the protrusion or the hard particles has to be repeated a plurality of times, thereby increasing a required forming time and resulting in inefficiency in the

formation of the ultrafine crystal layer. On the other hand, in the ultrafine crystal layer forming process defined in the first aspect of the invention, since the ultrafine crystal layer is formed by performing the machining operation using the machining tool, it is possible to efficiently form the ultrafine crystal layer, leading to the consequent reduction in the cost ~~for the formation of the ultrafine crystal layer~~.

[0033] Further, since the machining operation using the machining tool causes the machined surface of the workpiece to be subjected to a plastic working ~~that causes the machined surface of the workpiece to have~~ <u>with</u> the true strain of at least 1, there is ~~en effect~~ <u>an effect</u> that ~~restrains~~ <u>reduces</u> a load exerted on the machining tool and a machine ~~in~~ <u>by</u> which the machining operation is performed. Consequently, even ~~where~~ <u>when</u> the workpiece to be machined is constituted by a material having a high hardness, it is possible to ~~restrain~~ <u>avoid</u> breakage of the machining tool, thereby providing an effect that enables the ultrafine crystal layer to be stably formed in the surface layer portion of the machined surface of the workpiece.

[0034] In the ultrafine crystal layer forming process defined in the second aspect of the invention, in addition to the effects provided in ~~the ultrafine crystal layer forming process defined in~~ the first aspect of the invention, the machining operation using the machining tool is performed with

a material temperature at the machined surface of the workpiece being held lower than a predetermined upper limit temperature, wherein the predetermined upper limit temperature is, ~~where~~ when the workpiece is constituted by a steel material, an Ac1 transformation point of the steel material, and wherein the predetermined upper limit temperature is, ~~where~~ when the workpiece is constituted by the metallic material other than the steel material, substantially half a melting point of the metallic material as expressed in terms of absolute temperature. Consequently, there is an effect that it is possible to stably form the ultrafine crystal layer in the surface layer portion of the machined surface of the workpiece that is constituted by a material having a relatively low hardness.

[0035] In the ultrafine crystal layer forming process defined in the third aspect of the invention, in addition to the effects provided in ~~the ultrafine crystal layer forming process defined in~~ the first aspect of the invention, the machining operation using the machining tool is performed with a material temperature at the machined surface of the workpiece being held within a predetermined temperature range, wherein the predetermined temperature range is, ~~where~~ when the workpiece is constituted by a steel material, not lower than an Ac1 transformation point of the steel material and is lower than a melting point of the steel material, and wherein the

predetermined temperature range is, ~~where~~ when the workpiece is constituted by the metallic material other than the steel material, not lower than substantially half a melting point of the metallic material as expressed in terms of absolute temperature and is lower than the melting point of the metallic material.

[0036] Since the machined surface of the workpiece can be softened by thus raising the material temperature at the machined surface of the workpiece to a predetermined temperature or higher, there is an effect that the true strain of at least 1 can be assuredly imparted to the machined surface of the workpiece. Consequently, there is an effect that it is possible to stably form the ultrafine crystal layer in the surface layer portion of the machined surface of the workpiece, ~~with~~ while the machining tool ~~being restrained~~ is prevented from ~~be~~ being broken, even ~~where~~ when the machining operation is performed on the workpiece constituted by a material having a relatively high hardness.

[0037] In the ultrafine crystal layer forming process defined in the fourth aspect of the invention, in addition to the effects provided in ~~the ultrafine crystal layer forming process defined in~~ the third aspect of the invention, ~~where~~ when the workpiece is constituted by the steel material, after the machining operation using the machining tool has been performed, the machined surface of the workpiece is cooled at

a rate higher than a cooling rate that is required for hardening the workpiece. Thus, there is an effect that the hardness of the ultrafine crystal layer can be held high.

[0038] In the ultrafine crystal layer forming process defined in the fifth aspect of the invention, in addition to the effects provided in ~~the ultrafine crystal layer forming process defined in~~ any one of the second through fourth aspects of the invention, the machining operation using the machining tool is performed, such that a material temperature at the machined surface of the workpiece is held lower than the predetermined upper limit temperature or held within the predetermined temperature range, and such that a material temperature at a non-ultrafine crystal layer ~~which is provided by~~ at a lower layer portion of the machined surface or ~~which is provided by~~ at a surface layer portion in neighborhood of the machined surface is held at least about 500 C° for a ~~length of~~ time ~~that is~~ not ~~larger~~ longer than about 1 second, for providing the non-ultrafine crystal layer with a hardness that is about 80 % as high as a hardness of a substrate of the workpiece.

[0040] In the machine component defined in the sixth aspect of the invention, the surface layer portion is at least partially provided ~~by~~ with the ultrafine crystal layer formed by the ultrafine crystal layer forming process defined in any one of the first through fifth aspects of the invention. Thus,

it is possible to improve a surface hardness of the machine component, and to improve a fatigue strength of the machine component owing to a compressive residual stress imparted thereto. Further, ~~a~~ wear resistance of the machine component can be improved, since it becomes ~~hard~~ difficult to be recrystallized even under a high temperature. Consequently, there is an effect that makes it possible to improve the characteristics of the machine component.

[0041] Further, since the ultrafine crystal layer is formed by the ultrafine crystal layer forming process defined in any one of the first through fifth aspects of the invention, the ultrafine crystal layer can be formed at a low cost, there is an effect that a cost ~~for the entirety of the machine component~~ of overall machine components as a product can be ~~restrained~~ reduced owing to the formation of the ultrafine crystal layer at the low cost.

[0042] In the machine component producing process defined in the seventh aspect of the invention, since there is provided at least the ~~ultrafine crystal layer forming~~ step of forming the ultrafine crystal layer in the machine component through the ultrafine crystal layer forming process defined in any one of the first through fifth aspects of the invention, there is an effect that the machine component can be produced with the ultrafine crystal layer being stably formed at a ~~restrained~~ low cost.

[0043] In the nanocrystal layer forming process defined in the eighth aspect of the invention, since the nanocrystal layer is formed in the surface layer portion of the machined surface by performing the machining operation using the machining tool, it is possible to ~~restrain~~ solve the problems, encountered in the conventional techniques, that portions of a workpiece in which the nanocrystal layer can be formed are limited ~~depending upon~~ by a shape of the workpiece and that the thickness and characteristics of the nanocrystal layer are not ~~uniform,~~ uniform. Consequently, the nanocrystal layer forming process provides an effect that makes it possible to stably form the nanocrystal layer ~~forming process~~ in the workpiece such as a machine component.

[0046] Further, the machining operation using the machining tool causes the machined surface of the workpiece to be subjected to the plastic working ~~that causes the machined surface of the workpiece to have~~ with the true strain of at least 7, and is performed with the material temperature at the machined surface of the workpiece being held within a predetermined temperature range, wherein the predetermined temperature range is, ~~where~~ when the workpiece is constituted by a steel material, not lower than an Ac1 transformation point of the steel material and is lower than a melting point of the steel material, and wherein the predetermined temperature range is, ~~where~~ when the workpiece is constituted

by the metallic material other than the steel material, not lower than substantially half a melting point of the metallic material as expressed in terms of absolute temperature and is lower than the melting point of the metallic material.

[0047] Thus, the machined surface of the workpiece can be softened by raising the material temperature at the machined surface of the workpiece to the predetermined temperature or higher, the true strain of at least 7 can be assuredly imparted to the machined surface of the workpiece, while restraining ~~restrains~~ a load exerted on the machining tool and a machine ~~in~~ by which the machining operation is performed. Consequently, even ~~where~~ when the workpiece to be machined is constituted by a material having a high hardness, it is possible to ~~restrain~~ avoid breakage of the machining tool, thereby providing an effect that enables the nanocrystal layer to be stably formed in the surface layer portion of the machined surface of the workpiece.

[0048] In the nanocrystal layer forming process defined in the ninth aspect of the invention, in addition to the effects provided in the ~~nanocrystal layer forming process defined in the~~ eighth aspect of the invention, the machining operation using the machining tool is performed, such that the material temperature at the machined surface of the workpiece is held within the predetermined temperature range, and such that the material temperature at a non-nanocrystal layer

located in the lower layer portion of the machined surface or located in the surface layer portion in neighborhood of the machined surface is held at least about 500 C° for the ~~length of~~ time ~~that is~~ not ~~larger~~ longer than about 1 second, for providing the nanocrystal layer with the hardness that is about 80 % as high as the hardness of the substrate of the workpiece.

[0050] In the nanocrystal layer forming process defined in the tenth aspect of the invention, since the nanocrystal layer is formed in the surface layer portion of the machined surface by performing the machining operation using the machining tool, it is possible to ~~restrain~~ solve the problems, encountered in the conventional techniques, that portions of a workpiece in which the nanocrystal layer can be formed are limited ~~depending upon~~ by a shape of the workpiece and that the thickness and characteristics of the nanocrystal layer are not ~~uniform,~~ uniform. Consequently, the nanocrystal layer forming process provides an effect that makes it possible to stably form the nanocrystal layer ~~forming process~~ in the workpiece such as a machine component.

[0053] In the nanocrystal layer forming process defined in the eleventh aspect of the invention, in addition to the effects provided in the ~~nanocrystal layer forming process defined in the~~ tenth aspect of the invention, the machining operation using the machining tool causes the machined surface

of the workpiece to be subjected to the plastic working ~~that causes the machined surface of the workpiece to have~~ with the true strain of at least 7, and is performed with the material temperature at the machined surface of the workpiece being held ~~not higher~~ lower than the predetermined upper limit temperature. Thus, there is an effect that the nanocrystal layer can be assuredly formed in the surface layer portion of the machined surface of the workpiece.

[0054] In the nanocrystal layer forming process defined in the twelfth aspect of the invention, in addition to the effects provided in the ~~nanocrystal layer forming process defined in the~~ eleventh aspect of the invention, the machining operation using the machining tool is performed with the material temperature at the machined surface of the workpiece being held such that the overall time-based average value of the material temperature during the machining operation and the overall surface-based average value of the material temperature in the entirety of the machined surface over which the heat is distributed are ~~not higher~~ lower than the predetermined upper limit temperature. That is, the material temperature may be increased to be momentarily or locally higher than the predetermined upper limit temperature, as long as the overall time-based and overall surface-based average values of the material temperature are held ~~not higher~~ lower than the predetermined upper limit temperature. It is

therefore possible to reduce a cost required for controlling the material temperature, thereby providing an effect that ~~restrains~~ reduces the cost for the formation of the nanocrystal layer.

[0055] In the nanocrystal layer forming process defined in the thirteenth aspect of the invention, in addition to the effects provided in ~~the nanocrystal layer forming process defined in~~ any one of the eighth through twelfth aspects of the invention, the machining operation using the machining tool is performed such that the strain gradient of at least 1 / μm is imparted to the surface layer portion of the machined surface. Thus, there is an effect that the nanocrystal layer can be assuredly formed in the surface layer portion of the machined surface of the workpiece.

[0056] In the machine component defined in the fourteenth aspect of the invention, the surface layer portion is at least partially provided ~~by~~ with the nanocrystal layer formed by the nanocrystal layer forming process defined in any one of the eighth through thirteenth aspects of the invention. Thus, it is possible to improve a surface hardness of the machine component, and to improve a fatigue strength of the machine component owing to a compressive residual stress imparted thereto. Further, ~~a~~ wear resistance of the machine component can be improved, since it becomes ~~hard~~ difficult to be recrystallized even under a high temperature. Consequently,

there is an effect that makes it possible to improve the characteristics of the machine component.

[0057] Further, since the nanocrystal layer is formed by the nanocrystal layer forming process defined in any one of the eighth through thirteenth aspects of the invention, the nanocrystal layer can be formed at a low cost, there is an effect that a cost ~~for the entirety of the machine component~~ of overall machine components as a product can be ~~restrained~~ reduced owing to the formation of the nanocrystal layer at the low cost.

[0058] In the machine component producing process defined in the fifteenth aspect of the invention, since there is provided at least the ~~nanocrystal layer forming~~ step of forming the nanocrystal layer in the machine component through the nanocrystal layer forming process defined in any one of the eighth through thirteenth aspects of the invention, there is an effect that the machine component can be produced with the nanocrystal layer being stably formed at a ~~restrained~~ low cost.

[0063] It ~~is~~ should be noted that the grain size (length) of the ultrafine crystal does not necessarily have to be from 100 nm to 1μm as measured in any directions, as long as it is from 100 nm to 1μm in at least one direction. That is, the ultrafine crystal does not necessarily have to be ~~provided by~~

a crystal circular in its cross section, but may be ~~provided by~~ a crystal having a flat shape in its cross section.

[0067] The first machining condition is ~~provided by a condition~~ that the inner circumferential surface of the hole 1 is subjected to a plastic working that causes the inner circumferential surface of the hole 1 to have a true strain of at least 1. This condition can be satisfied by performing the drilling operation in accordance with a cutting condition indicated by Fig. 2~~. The cutting condition will be described with reference to Fig.2.~~, which will be described here in more detail.

[0071] It is preferable that a feed amount of the drill D is ~~not larger~~ smaller than 0.3 mm per one revolution thereof, so that the plastic working of the true strain of at least 1 can be assuredly imparted to the inner circumferential surface of the hole 1, while a load exerted on the drill D is restrained.

[0072] It is preferable that the cutting condition as the first machining condition is that the peripheral velocity V of the drill D is ~~not lower~~ higher than (175 - H / 4) [m/min] with the feed amount of the drill D per one revolution thereof being not larger than 0.05 mm, ~~where~~ when the hardness H of the workpiece W is lower than 500 [Hv], and that the peripheral velocity V of the drill D is ~~not lower~~ higher than 75 [m/min] with the feed amount of the drill D per one

revolution thereof being ~~not larger~~ smaller than 0.05 mm, ~~where~~ when the hardness H of the workpiece W is ~~not lower~~ higher than 500 [Hv]. This cutting condition further assuredly causes the inner circumferential surface of the hole 1 to be subjected to the plastic working ~~that provides the inner circumferential surface~~ with the true strain of at least 1, while ~~restraining~~ reducing the load exerted on the drill D.

[0074] Specifically, the process may be initiated with formation of a prepared hole 2 (indicated by one-dot chain line in view (a) of Fig. 1) with a drill having a diameter that is smaller than a predetermined diameter. Then, the prepared hole 2 may be enlarged by the drill D or a reamer having diameter substantially equal to the predetermined diameter, so that the hole 1 is finished to have the predetermined diameter. The formation of the prepared hole 2 is made in accordance with an ordinary cutting condition (for example, at a peripheral velocity ~~of not higher that~~ lower than 20 [m/min]), while the finishing of the hole 1 with the drill D or the reamer is made in accordance with the first machining condition (cutting condition for forming the ultrafine crystal layer) as shown in Fig. 2.

[0075] The second machining condition is ~~provided by a condition~~ that a material temperature at the machined surface of the hole 1 is held within a predetermined temperature range (hereinafter referred to as "temperature

range") during the drilling operation with the drill D. That is, the material temperature at the machined surface of the hole 1 is held within the ~~predetermined~~ temperature range, by adjusting an amount of supply of cutting oil to a cutting portion and the cutting condition (such as the peripheral velocity V and the feed amount of the drill D).

[0076] ~~Where~~ When the workpiece W is constituted by a steel material, the temperature range is ~~not lower~~ higher than an Ac1 transformation point of the steel material and is lower than a melting point of the steel material. ~~Where~~ When the workpiece W is constituted by a metallic material (for example, aluminum alloy, titanium alloy) other than the steel material, the temperature range is ~~not lower~~ higher than substantially half a melting point of the metallic material and is lower than the melting point of the metallic material.

[0077] It ~~is~~ should be noted that the melting point is expressed in terms of absolute temperature. For example, ~~where~~ when the melting point is 1500 °C, a temperature substantially half the melting point is about 886.5 K (= 1773 K / 2).

[0080] Further, the workpiece W may be heated by heating means (for example, gas furnace and electric furnace) before the initiation of the machining of the hole 1 with the drill D. This facilitates the formation of the ultrafine crystal layer C1 and also softening of the workpiece W, reducing load applied to the drill D (machining tool) and a machining

apparatus and accordingly making it possible to ~~restrain~~ avoid their breakages.

[0083] Fig. 3 is a cross sectional view showing a structure of a portion of the workpiece W surrounding the hole 1. In the inner circumferential surface of the hole 1, as shown in Fig. 3, there ~~were observed~~ are a surface layer 11 and a second layer 12 that are arranged in the order of description in a direction away from the inner circumferential surface (in a direction away from an upper side as seen in Fig. 3). It ~~is~~ should be noted that there ~~was~~ is a non-machined region (region that is not influenced by the machining with the drill D) 13 located on a lower side of the second layer 12 (as seen in Fig. 3).

[0084] In the surface layer 11 defining the hole 1, there ~~was observed~~ is the ultrafine crystal layer C1 in which its grain size was about 600 nm. In this ultrafine crystal layer C1, it was confirmed that its hardness was increased to 1000 Hv. It is considered that the surface layer 11 was recrystallized in α phase by generated heat and then residue α was caused to have an island-like shape in a further heated phase, i.e., $(\alpha + \gamma)$ two-phases region during the machining operation with the drill D, and that eventually solid solution γ containing carbon was transformed to $(\alpha$ + martensite) during cooling after the machining operation. It is noted that a

plastic deformation with true strain of at least 1 was imparted to the surface layer 11.

[0091] Next, ~~there will be described~~ a result of a test for torsion fatigue strength is described, which was conducted in a case where the ultrafine crystal layer forming process according to the first embodiment was applied to production of an input shaft used in an automatic transmission. The input shaft is constituted by the material same as the above-described workpiece W, and is ~~provided by~~ formed of a long shaft having a horizontal hole formed therein. The horizontal hole extends in an axial direction of the shaft and serves to introduce lubricant oil.

[0092] In an outer circumferential surface of the input shaft, ~~there are formed~~ a plurality of branch holes ~~which~~ are held in communication with the horizontal hole and through which the lubricant oil is to be supplied. The branch holes were formed in accordance with the above-described ultrafine crystal layer forming process. Thus, an inner circumferential surface of each branch hole is provided ~~by~~ with the ultrafine crystal layer C1, and is accordingly provided with an improved hardness.

[0103] The ultrafine crystal layer forming process according to the third embodiment is a process of forming the ultrafine crystal layer C1 in the surface layer portion of the machined surface of the workpiece W ~~where~~ when the workpiece

W is constituted by a material having a relatively low hardness. Specifically, the ultrafine crystal layer C1 is formed in the surface layer portion ~~(surface layer portion of the machined surface)~~ of the machined surface (see view (b) of Fig. 5), by performing the slide machining operation (machining operation) on the workpiece W with the pressing tool P (machining tool), satisfying the above-described first machining condition (see view (a) of Fig. 5).

[0105] The third cutting condition is ~~provided by a condition~~ that a material temperature at a machined outer circumferential surface 21 is held lower than a predetermined temperature (hereinafter referred to as "upper limit temperature") during the slide machining operation with the pressing tool P. That is, the material temperature at the machined outer circumferential surface 21 is ~~restrained~~ prevented from being increased, by adjusting an amount of supply of a coolant to a machining portion and a rotation speed of the workpiece W.

[0106] ~~Where~~ When the workpiece W is constituted by a steel material, the upper limit temperature is an Ac1 transformation point of the steel material. ~~Where~~ When the workpiece W is constituted by a metallic material (for example, aluminum alloy, titanium alloy) other than the steel material, the upper limit temperature is substantially half a melting point of the metallic material. It ~~is~~ should be noted

that the melting point is expressed in terms of absolute temperature, as in the above-described cases.

[0114] In the workpiece W after the annealing treatment, the hardness in the inner portion in which the ultrafine crystal layer C1 was not formed was 1.5 GPa (150 Hv), while the hardness in the ultrafine crystal layer C1 was twice or higher, namely, ~~was~~ kept high. Thus, the crystal grains in the ultrafine crystal layer C1 are difficult to be recrystallized even by the annealing treatment, ~~so that~~ <u>and</u> the ultrafine crystal layer C1 is excellent in its temperature insensitivity. Therefore, by applying the ultrafine crystal layer forming process of the third embodiment to a sliding surface of a rotary shaft, it is possible to improve ~~a~~ wear resistance of the sliding surface and accordingly to lengthen a life of the rotary shaft.

[0122] It ~~is~~ <u>should be</u> noted that the grain size (length) of the nanocrystal does not necessarily have to be 100 nm or less as measured in any directions, as long as it is 100 nm or less as measured in at least one direction. That is, the nanocrystal does not necessarily have to be ~~provided by~~ a crystal circular in its cross section, but may be ~~provided by~~ a crystal having a flat shape in its cross section.

[0123] Further, the nanocrystal layer may be ~~provided by~~ a mixed grain structure, as long as a content of the

nanocrystal in the structure is at least 50%. The remainder of the structure may be constituted by any form of crystal.

[0126] The fourth machining condition is ~~provided by a condition~~ that the inner circumferential surface of the hole 1 is subjected to a plastic working that causes the inner circumferential surface of the hole 1 to have a true strain of at least 7. This condition can be satisfied by performing the drilling operation in accordance with a cutting condition indicated by Fig. 7~~. The cutting condition will be described with reference to Fig. 7~~, which will be described here.

[0131] A recommendable cutting condition (preferable condition for forming the nanocrystal layer C2) as the fourth machining condition is that the hardness H of the workpiece W is ~~lower~~ higher than 500 [Hv], and the peripheral velocity V of the drill D is ~~not lower~~ higher than 50 [m/min] with the feed amount of the drill D per one revolution thereof being ~~not larger~~ smaller than 0.2 mm.

[0132] A further recommendable cutting condition is that the hardness H of the workpiece W is ~~lower~~ higher than 500 [Hv], and the peripheral velocity V of the drill D is ~~not lower~~ higher than 75 [m/min] with the feed amount of the drill D per one revolution thereof being ~~not larger~~ smaller than 0.05 mm. This cutting condition further assuredly causes the inner circumferential surface of the hole 1 to be subjected to the plastic working ~~that provides the inner circumferential~~

~~surface~~ with the true strain of at least 7, while restraining the load exerted on the drill D.

[0134] Specifically, the process may be initiated with formation of a prepared hole 2 (indicated by one-dot chain line in view (a) of Fig. 6) with a drill having a diameter that is smaller than a predetermined diameter. Then, the prepared hole 2 may be enlarged by the drill D or a reamer having diameter substantially equal to the predetermined diameter, so that the hole 1 is finished to have the predetermined diameter. The formation of the prepared hole 2 is made in accordance with an ordinary cutting condition (for example, at a peripheral velocity ~~of not higher that~~ <u>lower than</u> 20 [m/min]), while the finishing of the hole 1 with the drill D or the reamer is made in accordance with the fourth machining condition (cutting condition for forming the nanocrystal layer) as shown in Fig. 7.

[0135] The fifth machining condition is ~~provided by a condition~~ that a material temperature at the machined surface of the hole 1 is held within a predetermined temperature range (hereinafter referred to as "temperature range") during the drilling operation with the drill D. That is, the material temperature at the machined surface of the hole 1 is held within the ~~predetermined~~ temperature range, by adjusting an amount of supply of cutting oil to a cutting portion and the

cutting condition (such as the peripheral velocity V and the feed amount of the drill D).

[0136] ~~Where~~ When the workpiece W is constituted by a steel material, the temperature range is ~~not lower~~ higher than an Ac1 transformation point of the steel material and is lower than a melting point of the steel material. ~~Where~~ When the workpiece W is constituted by a metallic material (for example, aluminum alloy, titanium alloy) other than the steel material, the temperature range is ~~not lower~~ higher than substantially half a melting point of the metallic material and is lower than the melting point of the metallic material.

[0137] It ~~is~~ should be noted that the melting point is expressed in terms of absolute temperature. For example, ~~where~~ when the melting point is 1500 °C, a temperature substantially half the melting point is about 886.5 K (= 1773 K / 2).

[0140] Further, the workpiece W may be heated by heating means (for example, gas furnace and electric furnace) before the initiation of the machining of the hole 1 with the drill D. This facilitates the formation of the nanocrystal layer C2 and also softening of the workpiece W, thereby reducing load applied to the drill D (machining tool) and a machining apparatus and accordingly making it possible to ~~restrain~~ avoid their breakages.

[0143] Fig. 8 is a cross sectional view showing a structure of a portion of the workpiece W surrounding the hole

1. In the inner circumferential surface of the hole 1, as shown in Fig. 8, there ~~were observed~~ are a surface layer 31, a second layer 32 and a third layer 33 that are arranged in the order of description in a direction away from the inner circumferential surface (in a direction away from an upper side as seen in Fig. 8). It ~~is~~ should be noted that there ~~was~~ is a non-machined region (region that is not influenced by the machining with the drill D) 14 located on a lower side of the third layer 33 (as seen in Fig. 8).

[0144] In the surface layer 31 defining the hole 1, there ~~was observed~~ is the nanocrystal layer C2 in which its grain size was about 20 nm. In this nanocrystal layer C2, it was confirmed that its hardness was increased to 1150 Hv. It is considered that the surface layer 31 was heated to γ phase and ~~had~~ experienced a large deformation (true strain of at least 7) so as to become fine γ grains during the drilling operation with the drill D, and that the nanocrystal layer C2 was formed as a result of diffusion transformation during cooling after the drilling operation.

[0145] In the second layer 32, there ~~was observed~~ is an ultrafine crystal layer in which its grain size was about 100 nm. In this ultrafine crystal layer, it was confirmed that its hardness was increased to 1000 Hv. It is considered that the second layer 32 was recrystallized in α phase by heat applied thereto during the machining operation and then residue α was

caused to have an island-like shape in a further heated phase, i.e., (α + γ) two-phases region, and that eventually solid solution γ containing carbon was transformed to (α + martensite) during the cooling. It is noted that a plastic deformation with true strain ~~of not smaller~~ larger than 1 (and smaller than 7) was imparted to the second layer 32.

[0146] In the fourth embodiment, a total ~~of~~ thickness ~~values~~ of the ~~respective~~ surface layer 31 and second layer 32 (depth as measured from the surface to a lower surface of the second layer 32) was about 10 μm. It was confirmed that the thickness values (depth) of such layers were increased with increase of the peripheral velocity V of the drill D. Further, it was confirmed that the thickness values (depth) of such layers were increased with increase of the diameter of the drill D ~~where~~ when the peripheral velocity V of the drill D was constant.

[0150] That is, with the strain gradient of 1 / μm being imparted to the surface layer portion, a dislocation density becomes about 10^{16} per one square meter. ~~Where~~ When the dislocation density becomes as high as such a degree, an energy required to cause the crystal to be fined becomes smaller than that required to cause a dislocation. Therefore, ~~where~~ when a further strain (deformation) is imparted by the machining operation to the workpiece W in such a state, it is possible to induce a transition of the state of the workpiece,

from its state in which the dislocation is caused, to its state in which the crystal is caused to be fined. Consequently, with the strain gradient of 1 / μm being imparted to the surface layer portion, it is possible to assuredly form the nanocrystal layer C2.

[0151] ~~Where~~ When a required value of the strain gradient is thus previously known, the cutting condition (e.g., cooling method, cutting speed, material hardness) may be adjusted based on the required value in the formation of the nanocrystal layer C2. Thus, the cutting condition can be determined ~~in view of~~ based on the strain gradient, so that the determination of the cutting condition can be made easily and efficiently, thereby making it possible to improve the operating efficiently.

[0155] It ~~is~~ should be noted that the material temperature at the machined surface during the drilling operation (machining operation) by the drill D is not particularly limited, as long as the drill operation can impart the strain gradient of at least 1 / μm to the surface layer portion of the machined surface. This is because, even ~~where~~ when the drilling operation does not satisfy the above-described fifth machining condition (that the material temperature at the machined surface is held within the predetermined temperature range), the nanocrystal layer C2 can be formed as long as the strain gradient of at least 1 / μm

can be imparted to the surface layer portion of the machined surface.

[0166] Next, ~~there will be described~~ a result of a test for torsion fatigue strength <u>is described</u>, which was conducted in a case where the nanocrystal layer forming process according to the fourth embodiment was applied to production of an input shaft used in an automatic transmission. The input shaft is constituted by the material same as the above-described workpiece W, and is ~~provided by~~ <u>formed of</u> a long shaft having a horizontal hole formed therein. The horizontal hole extends in an axial direction of the shaft and serves to introduce lubricant oil.

[0167] In an outer circumferential surface of the input shaft, ~~there are formed~~ a plurality of branch holes ~~which~~ are held in communication with the horizontal hole and through which the lubricant oil is to be supplied. The branch holes were formed in accordance with the above-described nanocrystal layer forming process. Thus, an inner circumferential surface of each branch hole is provided ~~by~~ <u>with</u> the nanocrystal layer C2, and is accordingly provided with an improved hardness.

[0186] The sixth machining condition is ~~provided by a condition~~ that the inner circumferential surface of the hole 1 is subjected to a plastic working that causes the inner circumferential surface of the hole 1 to have a true strain of at least 7. This condition can be satisfied by performing the

drilling operation in accordance with a cutting condition indicated by Fig. 14. It is noted that Fig. 14 is a view showing the sixth machining condition in the form of the cutting condition ~~(cutting condition for forming the nanocrystal layer)~~ for forming the nanocrystal layer, as compared with a conventional cutting condition, wherein the abscissa indicates a hardness (Hv) of the workpiece W, while the ordinate indicates a peripheral velocity (m/min) of the drill D.

[0190] The seventh machining condition is ~~provided by a condition~~ that a material temperature at the machined surface of the hole 1 is held lower than a predetermined temperature (hereinafter referred to as "upper limit temperature") during the drilling operation with the drill D. That is, by supplying cutting oil or the like to a machining portion, the material temperature at the machined surface is ~~restrained~~ prevented from being increased.

[0191] ~~Where~~ When the workpiece W is constituted by a steel material, the upper limit temperature is A1 and A3 transformation points of the steel material. ~~Where~~ When the workpiece W is constituted by a metallic material other than the steel material, the upper limit temperature is substantially half a melting point of the metallic material. It is noted that the melting point is expressed in terms of absolute temperature. For example, ~~where~~ when the melting

point is 1500 °C, a temperature substantially half the melting point is about 886.5 K (= 1773 K / 2).

[0195] Next, ~~there will be described~~ a result of a test for torsion fatigue strength <u>is described</u>, which was conducted in a case where the nanocrystal layer forming process according to the sixth embodiment was applied to production of an input shaft used in an automatic transmission. The input shaft is constituted by the material same as the above-described workpiece W, and is ~~provided by~~ <u>formed of</u> a long shaft having a horizontal hole formed therein. The horizontal hole extends in an axial direction of the shaft and serves to introduce lubricant oil.

[0196] In an outer circumferential surface of the input shaft, ~~there are formed~~ a plurality of branch holes ~~which~~ are held in communication with the horizontal hole and through which the lubricant oil is to be supplied. The branch holes were formed in accordance with the above-described nanocrystal layer forming process. Thus, an inner circumferential surface of each branch hole is provided ~~by~~ <u>with</u> the nanocrystal layer, and is accordingly provided with an improved hardness.

[0208] In the workpiece W after the annealing treatment, the hardness in the inner portion in which the nanocrystal layer C3 was not formed was 1.5 GPa (155 Hv), while the hardness in the nanocrystal layer C3 was 3.9 GPa (400 Hv), namely, ~~was~~ kept high. Thus, the crystal grains in the

nanocrystal layer C3 are difficult to be recrystallized even by the annealing treatment, ~~so that~~ and the nanocrystal layer C3 is excellent in its temperature insensitivity. Therefore, by applying the nanocrystal layer forming process of the seventh embodiment to a sliding surface of a rotary shaft, it is possible to improve ~~a~~ wear resistance of the sliding surface and accordingly to lengthen a life of the rotary shaft.

[0211] For example, in the example of the sixth embodiment, since the nanocrystal layer C3 is formed concurrently with the formation of the hole 1 by the drill D, there is no need to add a step for forming the nanocrystal layer C3. Further, in the example of the seventh embodiment, the nanocrystal layer C3 can be formed after ~~he~~ the outer circumferential surface 41 is cut by a lathe tool, by simply replacing the lathe tool with the pressing tool P, namely, by keeping the workpiece W to be held by the holder, so that modifications of the required process can be minimized.